Extravehicular Activity Operations and Advancements

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A dramatic expansion in extravehicular activity (EVA)—or "spacewalking"—capability occurred during the Space Shuttle Program; this capability will tremendously benefit future space exploration. Walking in space became almost a routine event during the program—a far cry from the extraordinary occurrence it had been. Engineers had to accommodate a new cadre of astronauts that included women, and the tasks these spacewalkers were asked to do proved significantly more challenging than before. Spacewalkers would be charged with building and repairing the International Space Station. Most of the early shuttle missions helped prepare astronauts, engineers, and flight controllers to tackle this series of complicated missions while also contributing to the success of many significant national resources—most notably the Hubble Space Telescope. Shuttle spacewalkers manipulated elements up to 9,000 kg (20,000 pounds), relocated and installed large replacement parts, captured and repaired failed satellites, and performed surgical-like repairs of delicate solar arrays, rotating joints, and sensitive Orbiter Thermal Protection System components. These new tasks presented unique challenges for the engineers and flight controllers charged with making EVAs happen.

The Space Shuttle Program matured the EVA capability with advances in operational techniques, suit and tool versatility and function, training techniques and venues, and physiological protocols to protect astronauts while providing better operational efficiency. Many of these advances were due to the sheer number of EVAs performed. Prior to the start of the program, 38 EVAs had been performed by all prior US spaceflights combined. The shuttle astronauts accomplished 157 EVAs.

This was the primary advancement in EVA during the shuttle era—an expansion of capability to include much more complicated and difficult tasks, with a much more diverse Astronaut Corps, done on a much more frequent basis. This will greatly benefit space programs in the future as they can rely on a more robust EVA capability than was previously possible.

Spacewalking: Extravehicular Activity

If We Can Put a Human on the Moon, Why Do We Need to Put One in the Payload Bay?

The first question for program managers at NASA in regard to extravehicular activities (EVAs) was: Are they necessary? Managers faced the challenge of justifying the added cost, weight, and risk of putting individual crew members outside and isolated from the pressurized cabin in what is essentially a personal spacecraft. Robotics or automation are often considered alternatives to sending a human outside the spacecraft; however, at the time the shuttle was designed, robotics and automation were not advanced enough to take the place of a human in all required external tasks. Just as construction workers and cranes are both needed to build skyscrapers, EVA crew members and robots are needed to work in space.

Early in the Space Shuttle Program, safety engineers identified several shuttle contingency tasks for which EVA was the only viable option. Several shuttle components could not meet redundancy requirements through automated means without an untenable increase in weight or system complexity. Therefore, EVA was employed as a backup. Once EVA capability was required, it became a viable and cost-effective backup option as NASA identified other system problems. Retrieval or repair of the Solar Maximum Satellite (SolarMax) and retrieval of the Palapa B2 and Westar VI satellites were EVA tasks identified very early in the program. Later, EVA became a standard backup option for many shuttle payloads, thereby saving cost and resolving design issues.

Gregory Harbaugh

Astronaut on STS-39 (1991), STS-54 (1993), and STS-82 (1997).
Manager, Extravehicular Activity (EVA) Office (1997-2001).

"In my opinion, one of the major achievements of the Space Shuttle era was the dramatic enhancement in productivity, adaptability, and efficiency of EVA, not to mention the numerous EVA-derived accomplishments. At the beginning of the shuttle era, the extravehicular mobility unit had minimal capability for tools, and overall utility of EVA was limited. However, over the course of the program EVA became a planned event on many missions and ultimately became the fallback option to address a multitude of on-orbit mission objectives and vehicle anomalies. Speaking as the EVA program manager for 4 years (1997-2001), this was the result of incredible reliability of the extravehicular mobility unit thanks to its manufacturers (Hamilton Sundstrand and ILC Dover), continuous interest and innovation led by the EVA crew member representatives, and amazing talent and can-do spirit of the engineering/training teams. In my 23 years with NASA, I found no team of NASA and contractor personnel more technically astute, more dedicated, more innovative, or more ultimately successful than the EVA team.

EVA became an indispensible part of the Space Shuttle Program. EVA could and did fix whatever problems arose, and became an assumed tool in the holster of the mission planners and managers. In fact, when I was EVA program manager we had shirts made with the acronym WOBTSYA—meaning 'we've only begun to save your Alpha' (the ISS name at the time). We knew when called upon we could handle just about anything that arose."

Automation and Extravehicular Activity

EVA remained the preferred method for many tasks because of its efficiency and its ability to respond to unexpected failures and contingencies. As amazing and capable as robots and automation are, they are typically efficient for anticipated tasks or those that fall within the parameters of known tasks. Designing and certifying a robot to perform tasks beyond known requirements is extremely costly and not yet mature enough to replace humans.

Robots and automation streamlined EVA tasks and complemented EVA, resulting in a flexible and robust capability for building, maintaining, and repairing space structures and conducting scientific research.

Designing the Spacesuit for the Space Shuttle

Once NASA established a requirement for EVA, engineers set out to design and build the hardware necessary to provide this capability. Foremost, a spacesuit was required to allow a crew member to venture outside the pressurized cabin. The Gemini and Apollo spacesuits were a great starting point; however, many changes were needed to create a workable suit for the shuttle. The shuttle suit had to be reusable, needed to fit many different crew members, and was required to last for many years of repeated use. Fortunately, engineers were able to take advantage of advanced technology and lessons learned from earlier programs to meet these new requirements.

Contingency extravehicular activity: Astronaut Scott Parazynski, atop the Space Station Robotic Arm and the Shuttle Robotic Arm extension, the Orbiter Boom Sensor System, approaches the International Space Station solar arrays to repair torn sections during STS-120 (2009).

The cornerstone design requirement for any spacesuit is to protect the crew member from the space environment.

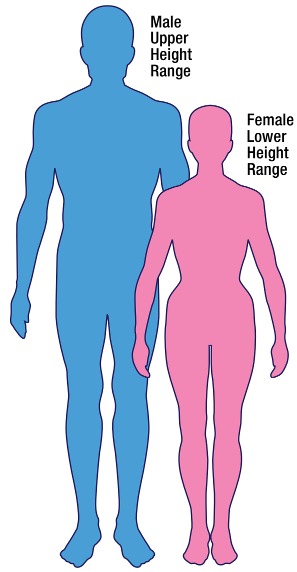
Suit Environment as Compared to Space Environment

Atmosphere	Suit Environment Requirements	Space Environment
Pressure:	23.44 kPa-27.57 kPa (3.4-4.4 psi)	1 Pa (1.45 x 10^{-4} psi)
Oxygen:	100%	0%
Temperature:	10°C-27°C (50°F-80°F)	-123°C-+232°C (-190°F-+450°F)

The target suit pressure was an exercise in balancing competing requirements. The minimum pressure required to sustain human life is 21.4 kPa (3.1 psi) at 100% oxygen. Higher suit pressure allows better oxygenation and decreases the risk of decompression sickness to the EVA crew member. Lower suit pressure increases crew member flexibility and dexterity, thereby reducing crew fatigue. This is similar to a water hose. A hose full of water is difficult to bend or twist, while an empty hose is much easier to move around. Higher suit pressures also require more structural stiffening to maintain suit integrity (just as a thicker balloon is required to hold more air). This further exacerbates the decrease in flexibility and dexterity. The final suit pressure selected was 29.6 kPa (4.3 psi), which has proven to be a reasonable compromise between these competing constraints.

The next significant design requirements came from the specific mission applications: what EVA tasks

Crew Member Size Variations and Ranges



Critical Body Dimension	5th % Female cm (in.)	95th % Male cm (in.)	Max. Size Variation cm (in.)
Standing Height	152.1 (59.9)	188.7 (74.3)	36.6 (14.4)
Chest Breadth	25.1 (9.9)	36.6 (14.4)	11.7 (4.6)
Chest Depth	20.8 (8.2)	27.7 (10.9)	6.9 (2.7)
Chest Circumference	82.3 (32.4)	109.7 (43.2)	27.4 (10.8)
Shoulder Circumference	95.5 (36.7)	128.5 (50.6)	35.3 (13.9)
Shoulder Breadth	38.6 (15.2)	46.7 (18.4)	8.1 (3.2)
Shoulder Height	122.9 (48.4)	156.7 (61.7)	33.8 (13.3)
Fingertip Span	152.4 (60.0)	195.6 (77.0)	43.2 (17.0)
Torso Length	56.1 (22.1)	70.4 (27.7)	14.2 (5.6)
Hip Breadth	31.5 (12.4)	38.9 (15.3)	7.4 (2.9)
Crotch Height	60.1 (26.8)	93.5 (36.8)	25.4 (10.0)
Knee Height	38.1 (15.0)	54.1 (21.3)	16.0 (6.3)

were required, who would perform them, and to what environmental conditions the spacewalkers would be exposed. Managers decided that the shuttle spacesuit would only be required to perform in microgravity and outside the shuttle cabin. This customized requirement allowed designers to optimize the spacesuit. The biggest advantage of this approach was that designers didn't have to worry as much about the mass of the suit.

Improving mobility was also a design goal for the shuttle extravehicular mobility unit (i.e., EVA suit). Designers added features to make it more flexible and allow the crew member greater range of motion than with previous suits. Bearings were included in the shoulder, upper arm, and waist areas to provide a useful range of mobility. The incorporation of the waist bearing enabled the EVA crew member to rotate.

Shuttle managers decided that, due to the duration of the program, the suit should also be reusable and able to fit many different crew members. Women were included as EVA crew members for the first time, necessitating unique accommodations and expanding the size range required. The range had to cover from the 5% American Female to the 95% American Male with variations in shoulders, waist, arms, and legs.

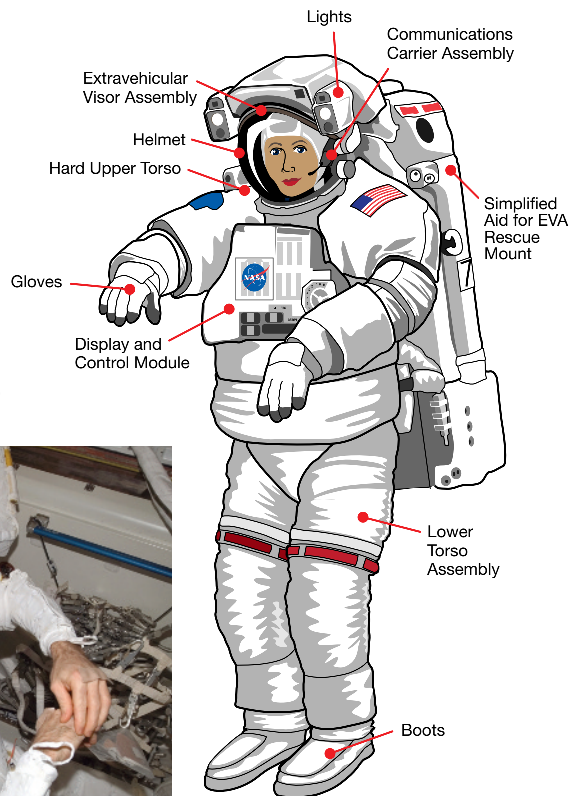
A modular "tuxedo" approach was used to address the multi-fit requirement. Tuxedos use several different pieces, which can be mixed and matched to best fit an individual—one size of pants can be paired with a different size shirt, cummerbund, and shoes to fit the individual. The EVA suit used a modular design, thereby allowing various pieces of different sizes to achieve a reasonably good fit. The design also incorporated a custom-tailoring capability using inserts, which allowed a reasonably good fit with minimal modifications.

While the final design didn't accommodate the entire size range of the Astronaut Corps, it was flexible enough to allow for a wide variety of crew members to perform spacewalks, especially those crew members who had the best physical attributes for work on the International Space Station (ISS).

One notable exception to this modular approach was the spacesuit gloves. Imagine trying to assemble a bicycle while wearing ski gloves that are too large and are inflated like a balloon. This is similar to attempting EVA tasks like driving bolts and operating latches while wearing an ill-fitting glove. Laser-scanning technology was used to provide a precise fit for glove manufacture patterns. Eventually, it became too expensive to maintain a fully customized glove program. Engineers were able to develop a set of standard sizes with adjustments at critical joints to allow good dexterity at a much lower cost. In contrast, a single helmet size was deemed sufficient to fit the entire population without compromising a crew member's ability to perform tasks.

The responsibility for meeting the reuse requirement was borne primarily by the Primary Life Support System, or "backpack," which included equipment within the suit garment to control various life functions. The challenge

Extravehicular Mobility Unit



February 8, 2007: Astronaut Michael Lopez-Alegria, International Space Station Expedition 14 commander, dons a liquid cooling and ventilation garment to be worn under the extravehicular mobility unit. Here, he is preparing for the final of three sessions of extravehicular activity (EVA) in 9 days.

for Primary Life Support System designers was to provide a multiyear, 25-EVA system. This design challenge resulted in many innovations over previous programs.

One area that had to be improved to reduce maintenance was body temperature control. Both the Apollo and the shuttle EVA suit used a water cooling system with a series of tubes that carried chilled water and oxygen around the body to cool and ventilate the crew member. The shuttle EVA suit improved on the Apollo design by removing the water tubes from the body of the suit and putting them in a separate garment—the liquid cooling ventilation garment. This garment was a formfitting, stretchable undergarment (think long johns) that circulated water and oxygen supplied by the Primary Life Support System through about 91 m (300 ft) of flexible tubing. This component of the suit was easily replaceable, inexpensive, easy to manufacture, and available in several sizes.

Materials changes in the Primary Life Support System also helped to reduce maintenance and refurbishment requirements. Shuttle designers replaced the tubing in the liquid cooling ventilation garment with ethylene vinyl acetate to reduce impurities carried by the water into the system. The single change that likely contributed the most toward increasing component life and reducing maintenance requirements was the materials selection for the Primary Life Support System water tank bladder. The water tank bladder expanded and contracted as the water quantity changed during the EVA, and functioned as a barrier between the water and the oxygen system. Designers replaced the molded silicon bladder material with Flourel™, which leached fewer and less-corrosive effluents and was half as permeable to water, resulting in dryer bladder cavities. This meant less corrosion and cleaner filters—all resulting in longer life and less maintenance.

Using the Apollo EVA suit as the basis for the shuttle EVA suit design saved time and money. It also provided a better chance for success by using proven design. The changes that were incorporated, such as using a modular fit approach, including more robust materials, and taking advantage of advances in technology, helped meet the challenges of the Space Shuttle Program. These changes also resulted in a spacesuit that allowed different types of astronauts to perform more difficult EVA tasks over a 30-year program with very few significant problems.

Extravehicular Activity Mission Operations and Training—All Dressed Up, Time to Get to Work

If spacesuit designers were the outfitters of spacewalks, flight controllers, who also plan the EVAs and train the crew members, were the choreographers. Early in the program, EVAs resembled a solo dancer performing a single dance. As flights became more complicated, the choreography became more like a Broadway show—several dancers performing individual sequences, before coming together to dance in concert. On Broadway, the individual sequences have to be choreographed so that dancers come together at the right time. This choreography is similar to developing EVA timelines for a Hubble repair or an ISS assembly mission. The tasks had to be scheduled so that crew members could work individually when only one person was required for a task, but allow them to come together when they had a jointly executed task.

The goal was to make timelines as efficient as possible, accomplish as many tasks as possible, and avoid one crew member waiting idle until the other crew member finished a task. The most significant contribution of EVA operations during the shuttle era was the development of this ability to plan and train for a large number of interdependent and challenging EVA tasks during short periods of time. Over time, the difficulty increased to require interdependent spacewalks within a flight and finally interdependent spacewalks between flights. This culminated in the assembly and maintenance of the ISS, which required the most challenging series of EVAs to date.

The first shuttle EVAs were devoted to testing the tools and suit equipment that would be used in upcoming spacewalks. After suit/airlock problems scrubbed the first attempt, NASA conducted the first EVA since 1974 during Space Transportation System (STS)-6 on April 7, 1983. This EVA practiced some of the shuttle contingency tasks and exercised the suit and tools. The goal was to gain confidence and experience with the new EVA hardware. Then on STS-41B (1984), the second EVA flight tested some of the critical tools and techniques that would be used on upcoming spacewalks to retrieve and repair satellites. One of the highlights was a test of the manned maneuvering unit, a jet pack designed to allow EVA crew members to fly untethered, retrieve satellites, and return with the satellite to the payload bay for servicing. The manned maneuvering unit allowed an EVA crew member to perform precise maneuvering around a target and dock to a payload in need of servicing.

Shuttle Robotic Arm

Another highlight of the STS-41B EVAs was the first demonstration of an EVA crew member performing tasks while positioned at the end of the

Astronaut Bruce McCandless on STS 41B (1984) in the nitrogen-propelled manned maneuvering unit, completing an extravehicular activity. McCandless is floating without tethers attaching him to the shuttle.

Shuttle Robotic Arm. This capability was a major step in streamlining EVAs to come as it allowed a crew member to be moved from one worksite to another quickly. This capability saved the effort required to swap safety tethers during translation and set up and adjust foot restraints—sort of like being able to roll a chair to move around an office rather than having to switch from chair to chair. It was also a first step in evaluating how an EVA crew member affected the hardware with which he or she interacted.

The concern with riding the Shuttle Robotic Arm was ensuring that the EVA crew member did not damage the robotic arm's shoulder joint by imparting forces and moments at the end of the 15-m (50-ft) boom that didn't have much more mass than the crew member. Another concern was the motion that the Shuttle Robotic Arm could experience under EVA loads—similar to how a diving board bends and flexes as a diver bounces on its end. Too much motion could make it too difficult to perform EVA tasks and too time consuming to wait until the motion damps out. Since the arm joints were designed to slip before damage could occur and crew members would be able to sense a joint slip, the belief was that the arm had adequate safeguards to preclude damage.

Allowing a crew member to work from the end of the arm required analysis of the arm's ability to withstand EVA crew member forces. Since both the Shuttle Robotic Arm and the crew member were dynamic systems, the analysis could be complicated; however, experts agreed that any dynamic EVA load case with a static Shuttle Robotic Arm would be enveloped by the case of applying brakes to the arm at its worst-case runaway speed with a static EVA crew member on the end. After this analysis demonstrated that the Shuttle Robotic Arm would not be damaged, EVA crew members were permitted to work on it. Working from the Shuttle Robotic Arm became an important technique for performing EVAs.

Satellite Retrieval and Repair

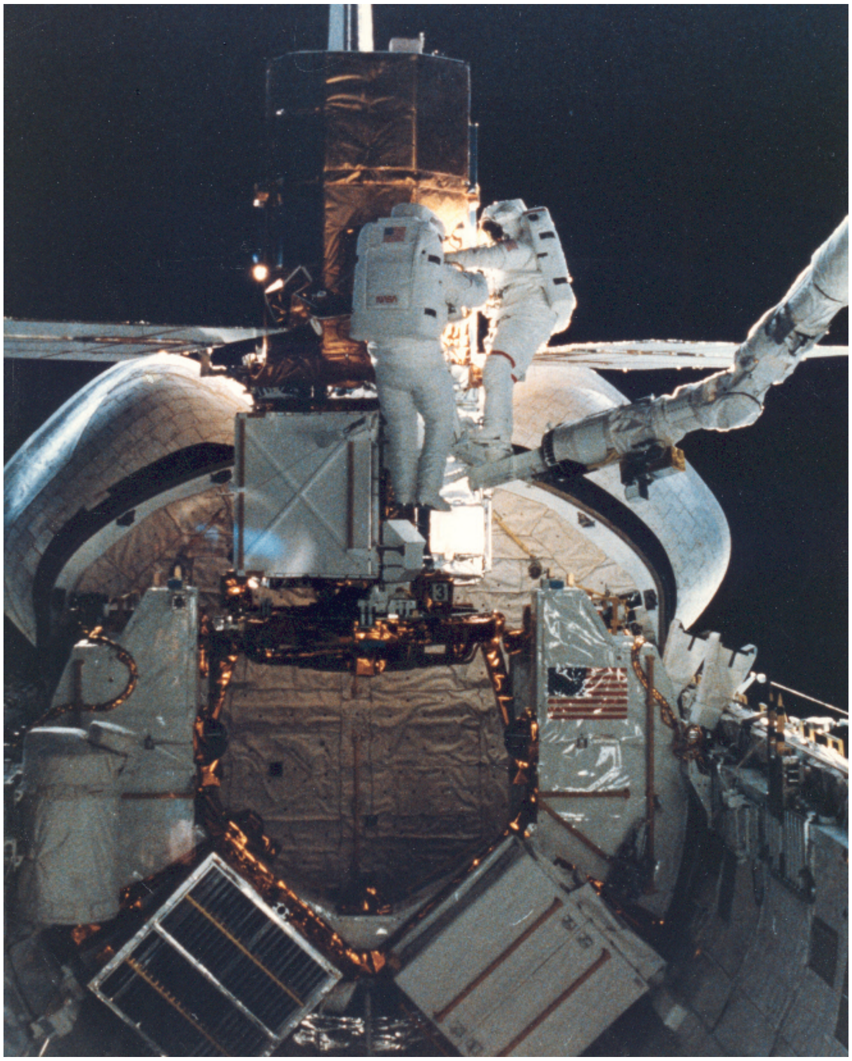
Once these demonstrations and tests of EVA capabilities were complete, the EVA community was ready to tackle satellite repairs. The first satellite to be repaired was SolarMax, on STS-41C (1984), 1 year after the first shuttle EVA. Shortly after STS-41B landed, NASA decided to add retrieval of Palapa B2 and Westar VI to the shuttle manifest, as the satellites had failed shortly after their deploy on that flight. While these early EVAs were ultimately successful, they did not go as originally planned.

NASA developed several new tools to assist in the retrieval. For SolarMax, the trunnion pin attachment device was built to attach to the manned maneuvering unit on one side and then mate to the SolarMax satellite on the other side to accommodate the towing of SolarMax back to the payload bay. Similarly, an apogee kick motor capture device (known as the "stinger") was built to attach to the manned maneuvering unit to mate with the Palapa B2 and Westar VI satellites. An a-frame was also provided to secure the Palapa B and Westar satellites in the payload bay. All was ready for the first operational EVAs; however, engineers, flight controllers, and managers would soon have their first of many experiences demonstrating the value of having a crew member in the loop.

When George Nelson flew the manned maneuvering unit to SolarMax during STS-41C, the trunnion pin attachment device jaws failed to close on the service module docking pins. After several attempts to mate, the action induced a slow spin and eventually an unpredictable tumble. SolarMax was stabilized by ground commands from Goddard Space Flight Center during the crew sleep period. The next day, Shuttle Robotic Arm operator Terry Hart grappled and berthed the satellite—a procedure that flight controllers felt was too risky preflight. EVA crew members executed a second EVA to complete the planned repairs.

The STS-51A (1984) Palapa B2/Westar VI retrieval mission was planned, trained, and executed within 10 months of the original satellite failures. In the wake of the problem retrieving SolarMax, flight planners decided to develop backup plans in case the crew had problems with the stinger or a-frame. Joseph Allen flew the manned maneuvering unit/stinger and mated it to the Palapa B2 satellite; however, Dale Gardner, working off the robotic arm, was unable to attach the a-frame device designed to assist in handling the satellite. The crew resorted to a backup plan, with Gardner grasping the satellite then slowly bringing it down and securing it for return to Earth. On a subsequent EVA, Gardner used the manned maneuvering unit and stinger to capture the Westar VI satellite, and the crew used the Shuttle Robotic Arm to maneuver it to the payload bay where the EVA crew members secured it.

Although the manned maneuvering unit was expected to be used extensively, the Shuttle Robotic Arm proved more



Astronauts George Nelson (right) and James van Hoften captured Solar Maximum Satellite in the aft end of the Challenger's cargo bay during STS-41C (1984). The purpose was to repair the satellite. They used the mobile foot restraint and the robotic arm for moving about the satellite.

efficient because it had fewer maintenance costs and less launch mass.

The next major EVA missions were STS-51D and STS-51I, both in 1985. STS-51D launched and deployed Syncom-IV/Leasat 3 satellite, which failed to activate after deployment. The STS-51D crew conducted the first unscheduled shuttle EVA. The goal was to install a device on the Shuttle Robotic Arm that would be used to attempt to flip a switch to activate the satellite. Although the EVA was successful, the satellite did not activate and STS-51I was replanned to attempt to repair the satellite. STS-51I was executed within 4 months of STS-51D, and two successful EVAs repaired it.

These early EVA flights were significant because they established many of the techniques that would be used throughout the Space Shuttle Program. They also helped fulfill the promise that the shuttle was a viable option for on-orbit repair of satellites. EVA flight controllers, engineers, and astronauts proved their ability to respond to unexpected circumstances and still accomplish mission objectives. EVA team members learned many things that would drive the program and payload customers for the rest of the program. They learned that moving massive objects was not as difficult as expected, and that working from the Shuttle Robotic Arm was a stable way of positioning an EVA crew member. Over the next several years, EVA operations were essentially a further extension of the same processes and operations developed and demonstrated on these early flights.

During the early part of the Space Shuttle Program, EVA was considered to be a last resort because of inherent risk. As the reliability and benefits of EVA were better understood, however, engineers began to have more confidence in it. They accepted that EVA could be employed as a backup means, be used to make repairs, or provide a way to save design complexity. Engineers were able to take advantage of the emerging EVA capability in the design of shuttle payloads. Payload designers could now include manual EVA overrides on deployable systems such as antennas and solar arrays instead of adding costly automated overrides. Spacecraft subsystems such as batteries and scientific instruments were designed to be repaired or replaced by EVA. Hubble and the Compton Gamma Ray Observatory were two notable science satellites that were able to use a significant number of EVA-serviceable components in their designs.

EVA flight controllers and engineers began looking ahead to approaching missions to build the ISS. To prepare for this, program managers approved a test program devoted to testing tools, techniques, and hardware design concepts for the ISS. In addition to direct feedback to the tool and station hardware designs, the EVA community gained valuable experience in planning, training, and conducting more frequent EVAs than in the early part of the program.

Hubble Repair

As NASA had proven the ability to execute EVAs and accomplish some remarkable tasks, demand for the EVA resource increased sharply on the agency. One of the most dramatic and demanding EVA flights began development shortly after the deployment of Hubble in April 1990. NASA's reputation was in jeopardy from the highly publicized Hubble failure, and the scientific community was sorely disappointed with the capability of the telescope. Hubble was designed with several servicing missions planned, but the first mission—to restore its optics to the expected performance—took on greater significance. EVA was the focal point in recovery efforts. The mission took nearly 3 years to plan, train, and develop the necessary replacement parts.

The Hubble repair effort required significant effort from most resources in the EVA community. Designers from Goddard Space Flight Center, Johnson Space Center, Marshall Space Flight

Three Spacewalkers Capture Satellite

Astronauts Rick Hieb on the starboard payload bay mounted foot restraint work station, Bruce Melnick with his back to the camera, and Tom Akers on the robotic arm mounted foot restraint work station—on the backside of the Intelsat during STS-49 (1992).

STS-49 significantly impacted planning for future EVAs. It was the most aggressive EVA flight planned, up to that point, with three EVAs scheduled. Engineers designed a bar with a grapple fixture to capture Intelsat and berth it in the payload bay. The data available on the satellite proved inadequate and it was modeled incorrectly for ground simulations. After two EVA attempts to attach the capture bar, flight controllers looked at other options.

The result was an unprecedented three-man EVA using space hardware to build a platform for the crew members, allowing them to position themselves in a triangle formation to capture the Intelsat by hand. This required an intense effort by ground controllers to verify that the airlock could fit three crew members, since it was only designed for two, and that there were sufficient resources to service all three. Additional analyses looked at whether there were sufficient handholds to grasp the satellite, that satellite temperatures would not exceed the glove temperature limits, and that structural margins were sufficient. Practice runs on the ground convinced ground operators that the operation was possible. The result was a successful capture and repair during the longest EVA in the shuttle era.

Center, and the European Space Agency delivered specialized tools and replacement parts for the repair. Approximately 150 new tools and replacement parts were required for this mission. Some of these tools and parts were the most complicated ones designed to date. Flight controllers concentrated on planning and training the unprecedented number of EVA tasks to be performed—a number that continued to grow until launch. What started as a three-EVA mission had grown to five by launch date. The EVA timeliners faced serious challenges in trying to accomplish so many tasks, as precious EVA resources were stretched to the limit.

New philosophies for managing EVA timelines developed in response to the growing task list. Until then, flight controllers included extra time in timelines to ensure all tasks would be completed, and crews were only trained in the tasks stated in those timelines. For Hubble, timelines included less flexibility and crews were trained on extra tasks to make sure they could get as much done as possible. With the next servicing mission years away, there was little to lose by training for extra tasks. To better ensure the success of the aggressive timelines, the crew logged more than twice the training time as on earlier flights.

Fatigue—A Constant Concern During Extravehicular Activity

Why are extravehicular activities (EVAs) so fatiguing if nothing has any weight in microgravity?

Lack of suit flexibility and dexterity forces the wearer to exert more energy to perform tasks. With the EVA glove, the fingers are fixed in a neutral position. Any motion that changes the finger/hand position requires effort.

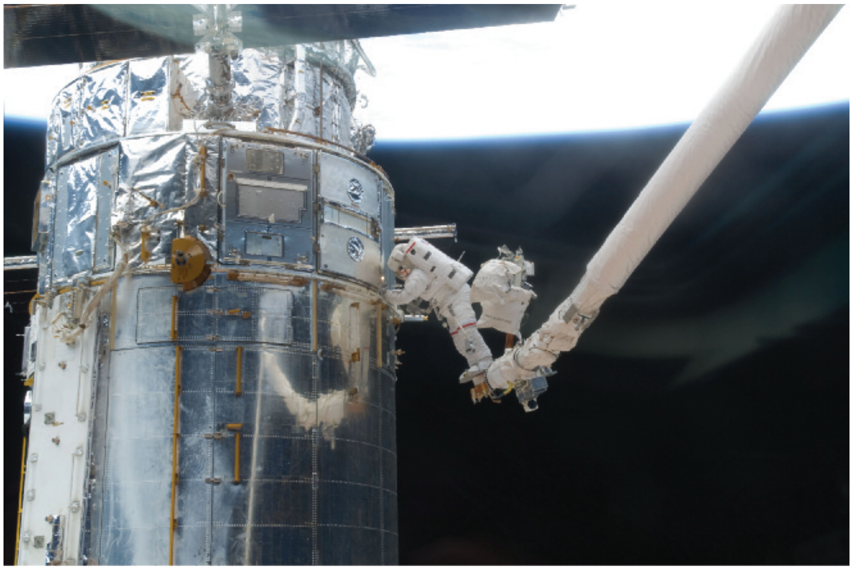
Lack of gravity removes leverage. Normally, torque used to turn a fastener is opposed by a counter-torque that is passively generated by the weight of the user. In weightlessness, a screwdriver user would spin aimlessly unless the user's arm and body were anchored to the worksite, or opposed the torque on the screwdriver with an equal muscular force in the opposite direction. Tool use during EVAs is accomplished by direct muscle opposition with the other arm, locking feet to the end of a robotic arm, or rigidly attaching the suit waist to the worksite. EVA tasks that require many hand/arm motions over several hours lead to significant forearm fatigue.

The most critical tasks—ingressing the airlock, shutting the hatch, and reconnecting the suit umbilical line— occur at the end of an EVA. Airlocks are cramped and tasks are difficult, especially when crew members are fatigued and overheated. Overheating occurs because the cooling system must be turned off before an astronaut can enter the airlock. The suit does not receive cooling until the airlock umbilical is connected. The helmet visor can fog over at this point, making ingress even more difficult.

Along with crew training, medical doctors and the mission control team monitor exertion level, heart rate, and oxygen usage. Communication between ground personnel and astronauts is essential in preventing fatigue from having disastrous consequences.

When astronauts were sent to the Hubble to perform its first repair, engineers became concerned that the crew members would put unacceptable forces on the great observatory. Engineers used several training platforms to measure forces and moments from many different crew members to gain a representative set of both normal and contingency EVA tasks. These cases were used to analyze Hubble for structural integrity and to sensitize EVA crew members to where and when they needed to be careful to avoid damage.

EVA operators also initiated three key processes that would prove very valuable both for Hubble and later for ISS. Operators and tool designers requested that, during Hubble assembly, all tools be checked for fit against all Hubble components and replacement parts. They also required extensive photography of all Hubble components and catalogued the images for ready access to aid in real-time troubleshooting. Finally, engineers analyzed all the bolts that would be actuated during the repair



Astronaut John Grunsfeld, working from the end of the Shuttle Robotic Arm, installs replacement parts on the Hubble Space Telescope during the final repair mission, STS-125 (2009).

to provide predetermined responses to problems operating bolts—data like the maximum torque allowed across the entire thermal range. Providing these data and fit checks would become a standard process for all future EVA-serviceable hardware.

The first Hubble repair mission was hugely successful, restoring Hubble's functionality and NASA's reputation. The mission also flushed out many process changes that the EVA community would need to adapt as the shuttle prepared to undertake assembly of the ISS. What had been a near disaster for NASA when Hubble was deployed turned out to be a tremendous opportunity for engineers, flight controllers, and mission managers to exercise a station-like EVA mission prior to when such missions would become routine. This mission helped demonstrate NASA's ability to execute a complex mission while under tremendous pressure to restore a vital international resource.

Flight Training

Once NASA identified the tasks for a shuttle mission, the crew had to be trained to perform them. From past programs, EVA instructors knew that the most effective training for microgravity took place under water, where hardware and crew members could be made neutrally buoyant. The Weightless Environment Training Facility— a swimming pool that measured 23 m (75 ft) long, 15 m (50 ft) wide, and 8 m (25 ft) deep—was the primary location for EVA training early in the Space Shuttle Program. The Weightless Environment Training Facility contained a full-size mock-up of the shuttle payload bay with all EVA interfaces represented. In the same manner that scuba divers use buoyancy compensation vests and weights, crew members and their tools were configured to be neutrally buoyant through the use of air, foam inserts, and weights. This enabled them to float suspended at the worksite, thus simulating a weightless environment.

Crew members trained an average of 10 hours in the Weightless Environment Training Facility for every 1 hour of planned on-orbit EVA. For complicated flights, as with the first Hubble repair mission, the training ratio was increased. Later, EVA training moved to a new, larger, and more updated water tank—the Neutral Buoyancy Laboratory—to accommodate training on the ISS.

A few limitations to the neutral buoyancy training kept it from being a perfect zero-gravity simulation. The water drag made it less accurate for simulating the movement of large objects. And since they were still in a gravity environment, crew members had to maintain a "heads-up" orientation most of the time to avoid blood pooling in the head. So mock-ups had to be built and oriented to allow crew members to maintain this position.

The gravity environment of the water tank also contributed to shoulder injuries—a chronic issue, especially in the latter part of the program. Starting in the mid 1990s, several crew members experienced shoulder injuries during the course of their EVA training. This was due to a design change made at that time to the extravehicular mobility unit shoulder joint. The shoulder joint was optimized for mobility, but designers noticed wear in the fabric components of the original joint. To avoid the risk of a catastrophic suit depressurization, NASA replaced the joint with a scye bearing that was much less subject to wear but limited to rotation in a single plane, thus reducing the range of motion. The scye bearing had to be placed to provide good motion for work and allow the wearer to don the extravehicular mobility unit through the waist ring (like putting on a shirt),

Astronaut Dafydd Williams, STS-118, representing the Canadian Space Agency, is wearing a training version of the extravehicular mobility unit spacesuit while participating in an underwater simulation of extravehicular activity in the Neutral Buoyancy Laboratory near Johnson Space Center. Scuba-equipped divers are in the water to assist Williams in his rehearsal, intended to help prepare him for work on the exterior of the International Space Station. Observe Williams holding the Pistol Grip Tool in his left hand with his shoulder extended. This position causes shoulder pain during training in neutral bouyancy.

which placed the arms straight up alongside the head. Placement of the shoulder joint was critical to a good fit, but there were only a few sizes of upper torsos for all crew members. Some crew members had reasonably good fit with the new joint, but others suffered awkward placement of the ring, which exerted abnormal forces on the shoulders. This was more a problem during training, when stress on the shoulder joint was increased due to gravity.

On Earth, the upper arm is held fairly close to the body during work activities. The shoulder joint is least prone to injury in this position under gravity. In space, the natural position of the arms is quite different, with arms extended in front of the torso. Shoulders were not significantly stressed by EVA tasks performed in microgravity. In ground training, however, it was difficult to make EVA tools and equipment completely neutrally buoyant, so astronauts often held heavy tools with their shoulders fully extended for long periods. Rotator cuff injuries, tendonitis, and other shoulder injuries occurred despite best efforts to prevent them. The problem was never fully resolved during the shuttle era, given the design limitations of the EVA suit and the intensity of training required for mission success.

The Precision Air Bearing Floor, also used for EVA training, is a 6-m (20-ft) by 9-m (30-ft), highly polished steel floor that works on the same principles as an air hockey table. Large mock-ups of flight hardware were attached to steel plates that had high-pressure air forced through tubes that ran along the bottom and sides. These formed a cushion under the mock-up that allowed the mock-up to move easily in the horizontal plane, simulating zero-gravity mass handling. Despite the single plane limitation of the Precision Air Bearing Floor, when combined with neutral buoyancy training the two facilities provided comprehensive and valuable training of moving large objects.

Another training and engineering platform was the zero-gravity aircraft. This specially outfitted KC-135 (later replaced by a DC-9) aircraft was able to fly a parabolic trajectory that provided approximately 20 seconds of microgravity on the downward slope, similar to the brief periods experienced on a roller coaster. This platform was not limited by water drag as was the Weightless Environment Training Facility, or to single plane evaluations as was the Precision Air Bearing Floor; however, it was only effective for short-duration tasks. Therefore, the zero-gravity aircraft was only used for short events that required a high-fidelity platform.

Extravehicular Activity Tools

EVA tools and support equipment are the Rodney Dangerfield of spacewalks. When they work, they are virtually unnoticed; however, when they fail to live up to expectations, everyone knows. Looking at the cost of what appear to be simple tools, similar to what might be found at the local hardware store, one wonders why they cost so much and don’t always work. The reality is that EVA tool engineers had a formidable task—to design tools that could operate, in vacuum, in temperatures both colder than the Arctic and as hot as an oven, and be operable by someone wearing the equivalent of several pairs of ski gloves, in vacuum, while weightless. These factors combined to produce a set of competing constraints that was difficult to balance. When adding that the complete space environment cannot be simulated on the ground, the challenge for building specialized tools that perform in space became clear. Any discussion of tools invariably involves the reasons why they fail and the lessons learned from those failures.

EVA tools are identified from two sources: the required EVA tasks, and engineering judgment on what general tools might be useful for unplanned events. Many of the initial tools were fairly simple—tethers, foot restraints, sockets, and wrenches. There were also specialized tools devoted to closing and latching the payload bay doors. Many tools were commercial tools available to the public but that were modified for use in space. This was thought to be a cost savings since they were designed for many of the same functions. These tools proved to be adequate for many uses; however, detailed information was often unavailable for commercial tools and they did not generally hold up to the temperature extremes of space. Material impurities made them unpredictable at cold temperatures and lubricants became too runny at high temperatures, causing failures. Therefore, engineers moved toward custom tools made with high-grade materials that were reliable across the full temperature range.

Trunnion pin attachment device, a-frame, and capture bar problems on the early satellite repair flights were found to be primarily due to incorrect information on the satellite interfaces. Engineers determined that interfering objects weren't represented on satellite design drawings. After these events, engineers stepped up efforts to better document EVA interfaces, but it is never possible to fully document the precise configuration of any individual spacecraft. Sometimes drawings include a range of options for components for which many units will be produced, and that will be manufactured over a long period of time. Designers must also have the flexibility to perform quick fixes to minor problems to maintain launch schedules. The balance between providing precise documentation and allowing design and processing flexibility will always be a judgment call and will, at times, result in problems.

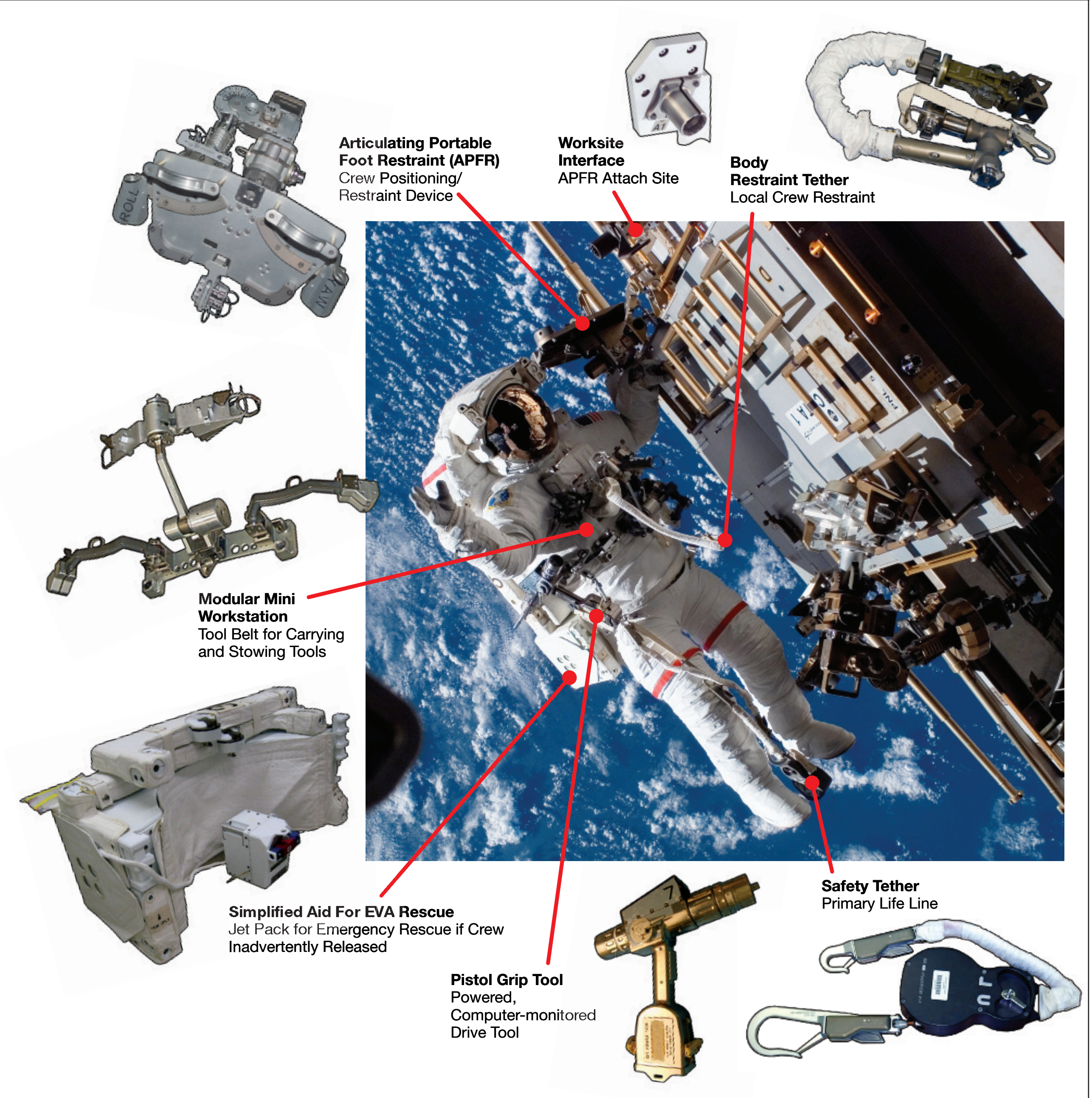
Engineers modified tools as they learned about the tools' performance in space. White paint was originally used as a thermal coating to keep tools from getting too hot. Since tools bump against objects and the paint tends to chip, the paint did not hold up well under normal EVA operations. Engineers thus switched to an anodizing process (similar to electroplating) to make the tools more durable. Lubricants were also a problem. Oil-based lubricants would get too thick in cold temperatures and inhibit moving parts from operating. In warm environments, the lubricants would become too thin. Dry-film lubricants (primarily Braycote®, which acts like Teflon® on frying pans) became the choice for almost all EVA tools because they are not vulnerable to temperature changes in the space environment.

Pistol Grip Tool

Some of the biggest problems with tools came from attempting to expand their use beyond the original purpose. Sometimes new uses were very similar to the original use, but the details were different—like trying to use a hacksaw to perform surgery. The saw is designed for cutting, but the precision required is extremely different. An example is the computerized Pistol Grip Tool, which was developed to actuate bolts while providing fairly precise torque information. This battery-operated tool was similar to a powered screwdriver, but had some sophisticated features to allow flexibility in applying and measuring different levels of torque or angular rotation. The tool was designed for Hubble, and the accuracy was more than adequate for Hubble. When ISS required a similar tool, the program chose to purchase several units of the Hubble power tool rather than design a new tool specific to ISS requirements. The standards for certification and documentation were different for Hubble. ISS had to reanalyze bolts, provide for additional ground and on-orbit processing of the Pistol Grip Tool to meet ISS accuracy needs, and provide additional units on orbit to meet fault tolerance requirements and maintain calibration.

The use of the Pistol Grip Tool for ISS assembly also uncovered another shortcoming with regard to using a tool developed for a different spacecraft. The Pistol Grip Tool was advertised as having an accuracy of 10% around the selected torque setting. This accuracy was verified by setting the Pistol Grip Tool in a fixed test stand on the ground where it was held rigidly in place. This was a valid characterization when used on Hubble where EVA worksites were designed to be easily accessible and where the Pistol Grip Tool was used directly on the bolts. It was relatively easy for crew members to center the tool and hold it steady on any bolt. ISS worksites were not as elegant as Hubble worksites, however, since ISS is such a large vehicle and the Pistol Grip Tool

Extravehicular Activity Tools



Astronaut Rick Mastracchio, STS-118 (2007), is shown using several extravehicular activity (EVA) tools while working on construction and maintenance of the International Space Station during the shuttle mission's third planned EVA activity.

often had to be used with socket extensions and other attachments that had inaccuracies of their own. Crew members often had to hold the tool off to the side with several attachments, and the resulting side forces could cause the torque measured by the tool to be very different than the torque actually applied. Unfortunately, ISS bolts were designed and analyzed to the advertised torque accuracy for Hubble and they didn't account for this "man-in-the-loop" effect. The result was a long test program to characterize the accuracy of the Pistol Grip Tool when used in representative ISS worksites, followed by analysis of the ISS bolts to this new accuracy.

To focus only on tool problems, however, is a disservice. It's like winning the Super Bowl and only talking about the fumbles. While use of the Pistol Grip Tool caused some problems as NASA learned about its properties, it was still the most sophisticated tool ever designed for EVA. It provided a way to deliver a variety of torque settings and accurately measure the torque delivered. Without this tool, the assembly and maintenance of the ISS would not have been possible.

Other Tools

NASA made other advancements in tool development as well. Tools built for previous programs were generally simple tools required for collecting geology samples. While there weren't many groundbreaking discoveries in the tool development area, the advances in tool function, storage, and transport greatly improved EVA efficiency during the course of the program. The fact that Henry Ford didn't invent the internal combustion engine doesn't mean he didn't make tremendous contributions to the automobile industry.

One area where tool engineers expanded EVA capabilities was in astronaut translation and worksite restraint. Improvements were made to the safety tether to include a more reliable winding device and locking crew hooks to prevent inadvertent release. Engineers developed portable foot restraints that could be moved from one location to another, like carrying a ladder from site to site. The foot restraints consisted of a boot plate to lock the crew member's feet in place and an adjustment knob to adjust the orientation of the plate for better positioning. The foot restraint had a probe to plug into a socket at the worksite. These foot restraints gave crew members the stability to work in an environment where unrestrained crew members would have otherwise been pushed away from the worksite whenever they exerted force.

The portable foot restraints were an excellent starting point, but they required a fair amount of time to move. They also became cumbersome when crew members had to work in many locations during a single EVA (as with the ISS). Engineers developed tools that could streamline the time to stabilize at a new location. The Body Restraint Tether is one of these tools. This tool consists of a stack of balls connected through its center by a cable with a clamp on one end to attach to a handrail and a bayonet probe on the other end to attach to the spacesuit. Similar to flexible shop lights, the Body Restraint Tether can be bent and twisted to the optimum position, then locked in that position with a knob that tightens the cable. The Body Restraint Tether is a much quicker way for crew members to secure themselves for lower-force tasks.

Another area where tool designers made improvements was tool stowage and transport. Crew members had to string tools to their suits for transport until designers developed sophisticated tool bags and boxes that allowed crews to carry a large number of tools and use the tools efficiently at a worksite. The Modular Mini Workstation—the EVA tool belt—was developed to attach to the extravehicular mobility unit and has become invaluable to conducting spacewalks. Specific tools can be attached to the arms on the workstation, thereby allowing ready access to the most-used tools. Various sizes of tool caddies and bags also help to transport tools and EVA "trash" (e.g., launch restraints).

Space Shuttle Program tool designers expanded tool options to include computer-operated electronics and improved methods for crew restraint, tool transport, and stowage. While there were hiccups along the way, the EVA tools and crew aids performed admirably and expanded NASA's ability to perform more complicated and increasingly congested EVAs.

Extravehicular Activity During Construction of the International Space Station

From 1981 through 1996, the Space Shuttle Program accomplished 33 EVAs. From 1997 through 2010, the program managed 126 EVAs devoted primarily to ISS assembly and maintenance, with several Hubble

Space Telescope repair missions also included. Assembly and maintenance of the ISS presented a series of challenges for the program. EVA tools and suits had to be turned around quickly and flawlessly from one flight to the next. Crew training had to be streamlined since several flights would be training at the same time and tasks were interdependent from one flight to the next. Plans for one flight, based on previous flight results, could change drastically just months (or weeks) before launch. Sharing resources with the International Space Station Program was also new territory—the same tools, spacesuits, and crew members would serve both programs after the ISS airlock was installed.

Medical Risks of Extravehicular Activity—Decompression Sickness

One risk spacewalkers share with scuba divers is decompression sickness, or "the bends." "The bends" name came from painful contortions of 19th-century underwater caisson workers suffering from decompression sickness, which occurs when nitrogen dissolves in blood and tissues while under pressure, and then expands when pressure is lowered. Decompression sickness can occur when spacewalkers exit the pressurized spacecraft into vacuum in a spacesuit

Decompression sickness can be prevented if nitrogen tissue concentrations are lowered prior to reducing pressure. Breathing 100% oxygen causes nitrogen to migrate from tissues into the bloodstream and lungs, exiting the body with exhaling. The first shuttle-based extravehicular activities used a 4-hour in-suit oxygen prebreathe. This idle time was inefficient and resulted in too long a crew day. New solutions were needed.

One solution was to lower shuttle cabin pressure from its nominal pressure of 101.2 kPa (14.7 psi) to 70.3 kPa (10.2 psi) for at least 12 hours prior to the EVA. This reduced cabin pressure protocol was efficient and effective, with only 40 minutes prebreathe.

Shuttle EVA crew members working International Space Station (ISS) construction required a different approach. It is impossible to reduce large volume ISS pressure to 70.3 kPa (10.2 psi). To increase the rate of nitrogen release from tissues, crew members exercised before EVA while breathing 100% oxygen. This worked, but it added extra time to the packed EVA day and exhausted the crew. Planners used the reduced cabin pressure protocol by isolating EVA crew members in the ISS airlock the night before the EVA and lowering the pressure to 70.3 kPa (10.2 psi). This worked well for the remainder of ISS EVAs, with no cases of decompression sickness throughout the Space Shuttle Program.

Extravehicular Loads for Structural Requirements

The EVA loads development program, first started for the Hubble servicing missions, helped define the ISS structural design requirements. ISS was the first program to have extensive EVA performed on a range of structural interfaces. The load cases for Hubble repair had to protect the telescope for a short period of EVA operations and for a finite number of well-known EVA tasks.

ISS load cases had to have sufficient margin for tasks that were only partially defined at the time the requirements were fixed, to protect for hundreds of EVAs over the planned life of the ISS. The size of ISS was also a factor. An EVA task on one end of the truss structure could be much more damaging than the same task closer to the center (just like bouncing on the end of a diving board creates more stress at the base than bouncing on the base itself). EVA loads had to account for intentional tasks (e.g., driving bolts) and unintentional events (e.g., pushing away from a rotating structure to avoid collision). Engineers had to protect for a reasonable set of EVA scenarios without overly restricting the ISS design to protect against simultaneous low-probability events. This required an iterative process that included working with ISS structures experts to zero in on the right requirements.

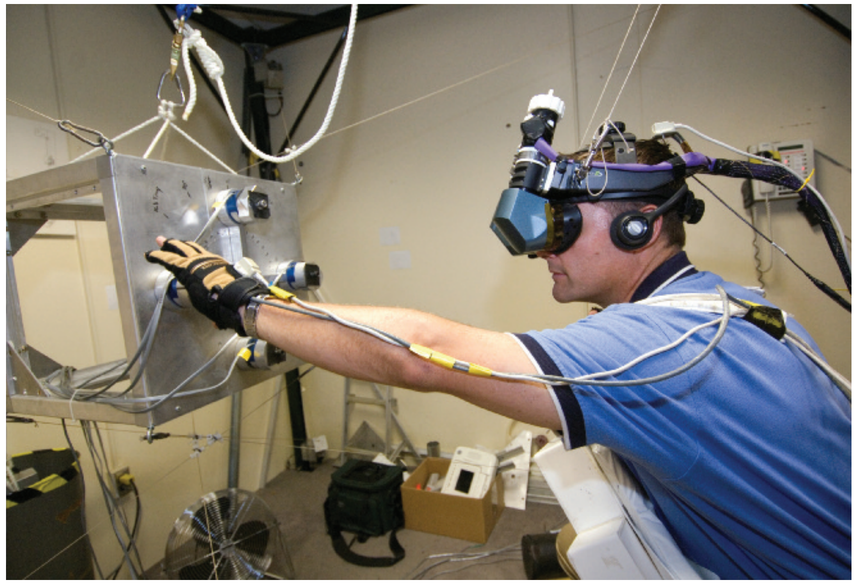
A considerable test program—using a range of EVA crew members executing a variety of tasks in different ground venues—characterized the forces and moments that an EVA crew member could impart. The resulting cases were used throughout the programs to evaluate new tasks when the tasks were needed. While the work was done primarily for ISS, the loads that had been developed were used extensively in the post-Columbia EVA inspection and repair development.

Rescue From Inadvertent Release

NASA always provided for rescue of an accidentally released EVA crew member by maintaining enough fuel to fly to him or her. Once ISS assembly began, however, the Orbiter was docked during EVAs and would not have been able to detach and pursue an EVA crew member in time. The ISS Program required a self-rescue jet pack for use during ISS EVAs. The Simplified Aid for EVA Rescue was designed to meet this requirement. Based on the manned maneuvering unit design but greatly simplified, the Simplified Aid for EVA Rescue was a reliable, nitrogen-propelled backpack that provided limited capability for a crew member to stop and fly back to the station or Orbiter. It was successfully tested on two shuttle flights when shuttle rescue was still possible if something went wrong. Fortunately, the Simplified Aid for EVA Rescue never had to be employed for crew rescue.

Extravehicular Activity Suit Life Extension and Multiuse Certification for International Space Station Support

A significant advancement for the EVA suit was the development of a regenerable carbon dioxide removal system. Prior to the ISS, NASA used single-use lithium hydroxide canisters for scrubbing carbon dioxide during an EVA. Multiple EVAs were routine during flights to the ISS. Providing a regenerative alternative using silver oxide produced significant savings in launch weight and volume. These canisters could be cleaned in the ISS airlock regenerator, thereby allowing the canisters to be left on orbit rather than processed on the ground and launched on the shuttle. This capability saved approximately 164 kg (361 pounds) up-mass per year.



Astronaut Douglas Wheelock, STS-120 (2007), uses virtual reality hardware in the Space Vehicle Mockup Facility at Johnson Space Center to rehearse some of his duties on the upcoming mission to the International Space Station.

Training Capability Enhancements

During the early shuttle missions, the Weightless Environment Training Facility and Precision Air Bearing Facility were sufficient for crew training. To prepare for space station assembly, however, virtually every mission would include training for three to five EVAs—often with two EVA teams—with training for three to five flights in progress simultaneously.

To do this, NASA built the Neutral Buoyancy Laboratory to accommodate EVA training for both the Space Shuttle and ISS Programs. At 62 m (202 ft) long, 31 m (102 ft) wide, and 12 m (40 ft) deep, the Neutral Buoyancy Laboratory is more than twice the size of the previous facility, and it dramatically increased neutral buoyancy training capability. It also allowed two simultaneous simulations to be conducted using two separate control rooms to manage each individual event.

Trainers took advantage of other resources not originally designed for EVA training. The Virtual Reality Laboratory, which was designed primarily to assist in robotic operations, became a regular EVA training venue. This lab helped crew members train in an environment that resembled the space environment, from a crew member's viewpoint, by using payload and vehicle engineering models working with computer software to display a view that changed as the crew member "moved" around the space station.

The Virtual Reality Laboratory also provided mass simulation capability by using a system of cables and pulleys controlled by a computer as well as special goggles to give the right visual cues to the crew member, thus allowing him or her to get a sense of moving a large object in a microgravity environment. Most of the models used in the Virtual Reality Laboratory were actually built for other engineering facilities, so the data were readily available and parameters could be changed relatively quickly to account for hardware or environment changes. This gave the lab a distinct advantage over other venues that could not accommodate changes as quickly.

In addition to the new training venues, changes in training philosophy were required to support ISS assembly. Typically, EVA crew training began at least 1 year prior to the scheduled launch. Therefore, crew members for four to five missions would have to train at the same time, and the tasks required were completely dependent on the previous flights' accomplishments. A hiccup in on-orbit operations could cascade to all subsequent flights, changing the tasks that were currently in training. In addition, on-orbit ISS failures often resulted in changes to the tasks, as repair of those components may have taken a higher priority.

To accommodate late changes, flight controllers concentrated on training individual tasks rather than timelines early in the training schedule. They also engaged in skills training—training the crew on general skills required to perform EVAs on the ISS rather than individual tasks. Flight controllers still developed timelines, but they held off training the timelines until closer to flight. Crews also trained on "get-ahead" tasks—those tasks that did not fit into the pre-mission timelines but that could be added if time became available. This flexibility provided time to allow for real-time difficulties.

Extravehicular Activity Participation in Return to Flight After Space Shuttle Columbia Accident

One other significant EVA accomplishment was the development of a repair capability for the Orbiter Thermal Protection System after the Space Shuttle Columbia accident in 2003. This posed a significant challenge for EVA for several reasons. The Thermal Protection System was a complex design that was resistant to high temperatures but was also delicate. It was located in areas under the fuselage that was inaccessible to EVA crew members. The materials used for repair were a challenge to work with, even in an Earth environment, since they did not adhere well to the damage. Finally, the repair had to be smooth since even very small rough edges or large surface deviations could cause turbulent airflow behind the repair, like rocks disrupting flow in a stream. Turbulent flow increased surface heating dramatically, with potentially disastrous results. These challenges, along with the schedule pressure to resume building and resupplying the ISS, made Thermal Protection System repair a top priority for EVA for several years.

The process included using repair materials that engineers originally began developing at the beginning of the program that now had to be refined and certified for flight. Unique tools and equipment, crew procedures, and methods to ensure stabilizing the crew member at the worksite were required to apply the material. The tools mixed the two-part silicone rubber repair material but also kept it from hardening until it was dispensed in

Astronauts Robert Curbeam (foreground) and Rex Walheim (background) simulate tile repair, using materials and tools developed after the Space Shuttle Columbia accident, on board the zero-gravity training aircraft KC-135.

Astronaut Piers Sellers, STS-121 (2006), wearing a training version of the extravehicular mobility unit, participates in an extravehicular activity simulation while anchored on the end of the training version of the Shuttle Robotic Arm in the Space Vehicle Mockup Facility at Johnson Space Center (JSC). The arm has an attached 15-m (50-ft) boom used to reach underneath the Orbiter to access tiles. Lora Bailey (right), manager, JSC Engineering Tile Repair, assisted Sellers.

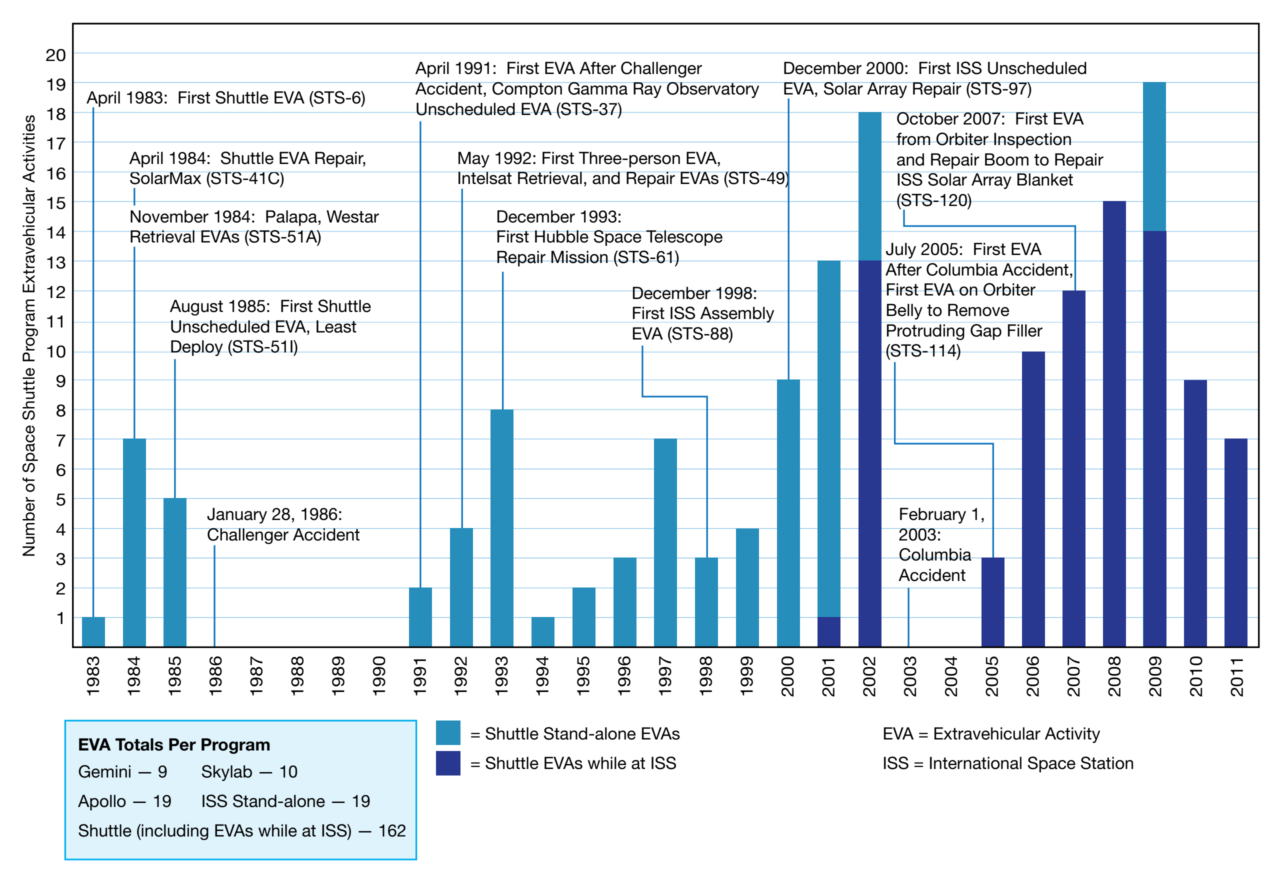
the damage area. The tools also maintained the materials within a fairly tight thermal range to keep them viable. Engineers were able to avoid the complexity of battery-powered heaters by selecting materials and coatings to passively control the material temperature. The reinforced carbon-carbon Thermal Protection System (used on the wing leading edge) repair required an additional set of tools and techniques with similar considerations regarding precision application of sensitive materials.

Getting a crew member to the worksite proved to be a unique challenge. NASA considered several options, including using the Simplified Aid for EVA Rescue with restraint aids attached by adhesives. Repair developers determined, however, that the best option was to use the new robotic arm extension boom provided for Orbiter inspection. The main challenge to using the extension boom was proving that it was stable enough to conduct repairs, and that the forces the EVA crew member imparted on the boom would not damage the boom or the arm. These concerns were similar to those involved with putting a crew member on a robotic arm, but the "diving board" was twice as long. The EVA loads work performed earlier provided a foundation for the process by which EVA loads could be determined for this situation; however, the process had to be modified since the work platform was much more flexible.

Previous investigations into EVA loads usually involved a crew member imparting loads into a fixed platform. When the loads were continuously applied to the boom/arm configuration, they resulted in a large (about 1.2 m [4 ft]) amount of sway as well as structural concerns for the arm and boom. Engineers knew that the boom/arm configuration was more like a diving board than a floor, meaning that the boom would slip away as force was applied, limiting the force a crew member could put into the system. Engineers developed a sophisticated boom/arm simulator and used it on the precision air bearing floor to measure EVA loads. These tests provided the data for analysis of the boom/arm motion. The work culminated in a flight test on STS-121 (2006), which demonstrated that the boom/arm was stable enough for repair and able to withstand reasonable EVA motions without damage.

Although the repair capability was never used, both the shuttle and the space station benefited from the repair development effort. Engineers made several minor repairs to the shuttle Thermal Protection System that would not have been possible without demonstrating that the EVA crew member could safely work near the fragile system. The boom was also used on the Space Station Robotic Arm to conduct a successful repair of a damaged station solar array wing that was not reachable any other way.

Major Extravehicular Activity Milestones



Summary

The legacy of EVA during the Space Shuttle Program consists of both the actual work that was done and the dramatic expansion of the EVA capability. EVA was used to successfully repair or restore significant national resources to their full capacity, such as Hubble, communications satellites, and the Orbiter, and to construct the ISS. EVA advanced from being a minor capability used sparingly to becoming a significant part of almost every shuttle mission, with an increasing list of tasks that EVA crew members were able to perform. EVA tools and support equipment provided more capability than ever before, with battery-powered and computer-controlled tools being well understood and highly reliable.

Much was learned about what an EVA crew member needs to survive and work in a harsh environment as well as how an EVA crew member affected his or her environment. This tremendous expansion in EVA capability will substantially benefit the future exploration of the solar system as engineers design vehicles and missions knowing that EVA crew members are able to do much more than they could at the beginning of the Space Shuttle Program.